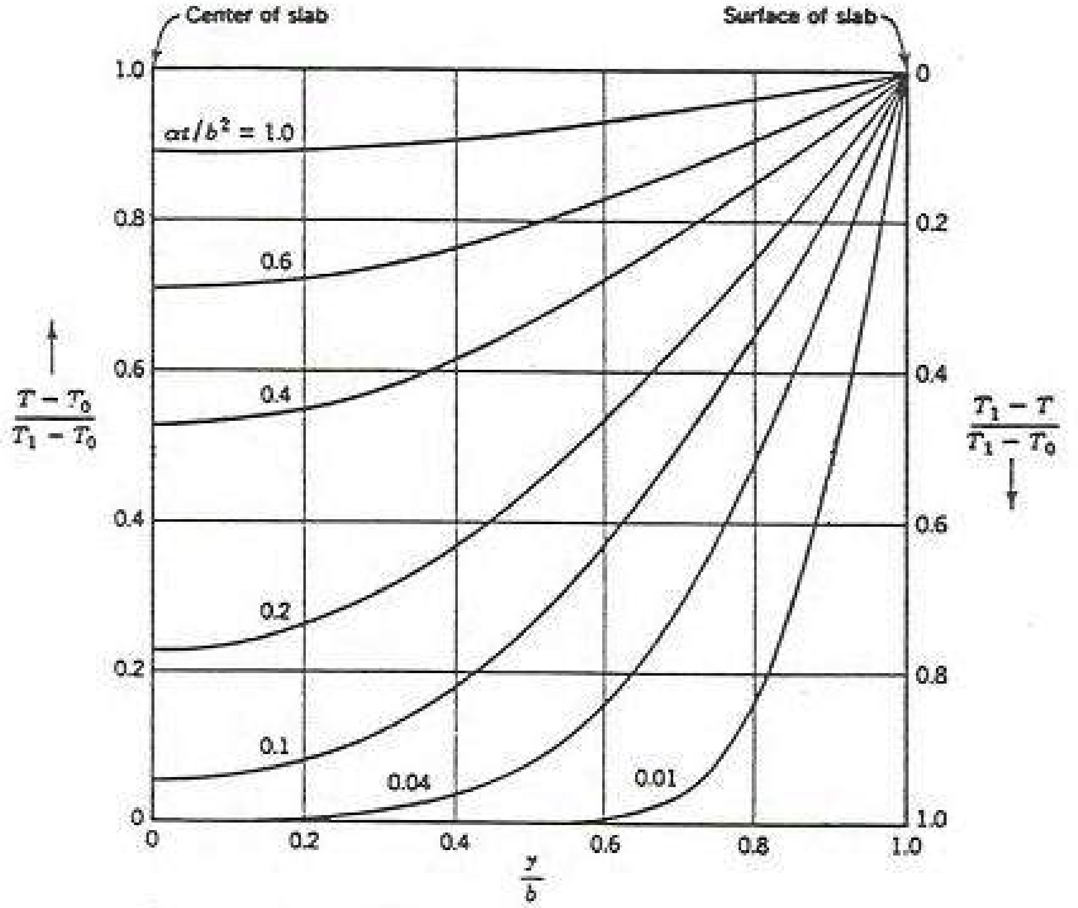
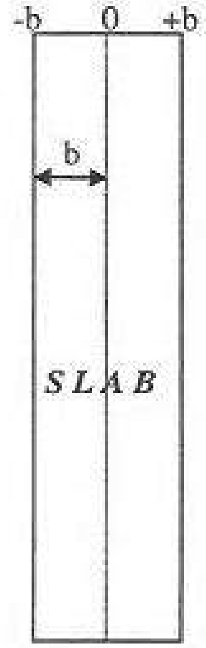
As can be seen from the equations presented, heat and mass transfer problems in rectangular, cylindrical and spherical situations can be solved … although the equations can (and are) very cumbersome. Fortunately, these equations have been solved for a variety of steady and unsteady state systems, many of which are of interest in food processing applications. Most notable are unsteady state heating and cooling of slabs, cylinders and spheres (like freezing a steak, retorting a can of soup, and quick freezing peas). Graphical solutions to some of these types of problems are illustrated in the next figures.





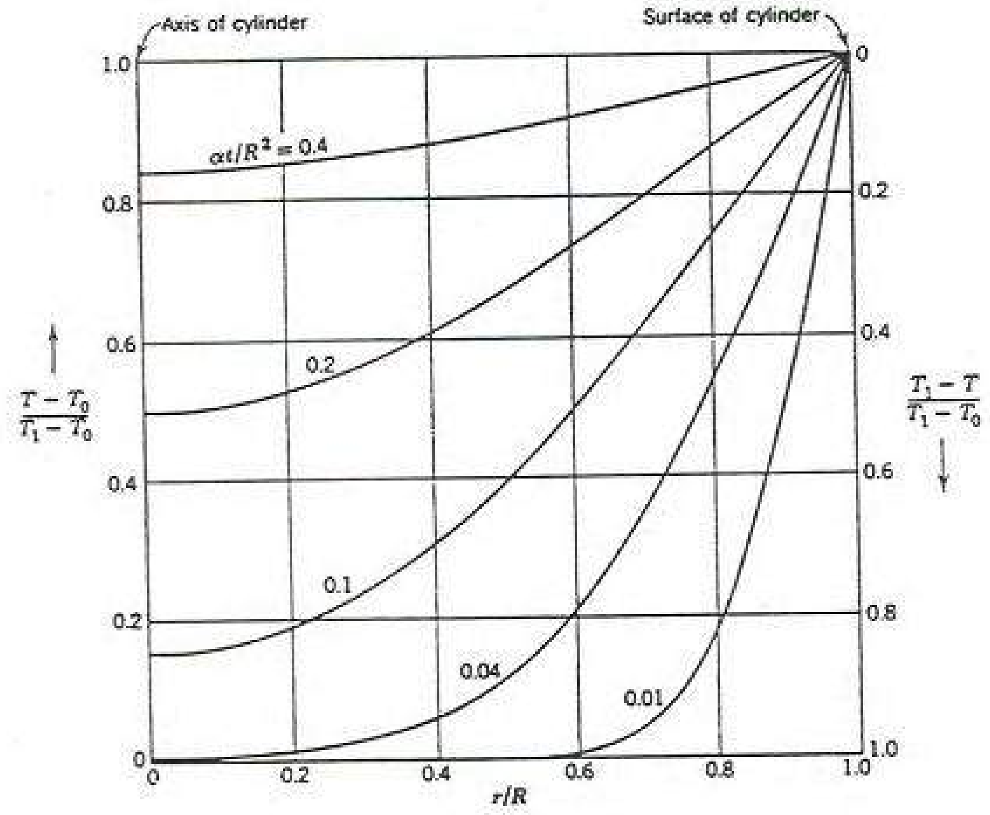
Temperature profiles for unsteady-state heat conduction in a slab of finite thickness. [H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids*, Oxford University Press (1959), p. 101.]

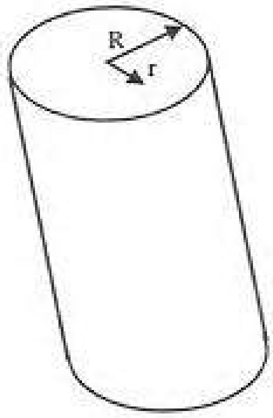
T = temperature at some location in the slab @ some time, t
T_o = initial slab temperature
T_1 = surface temperature @ time, t >0

Parameters used in the charts:

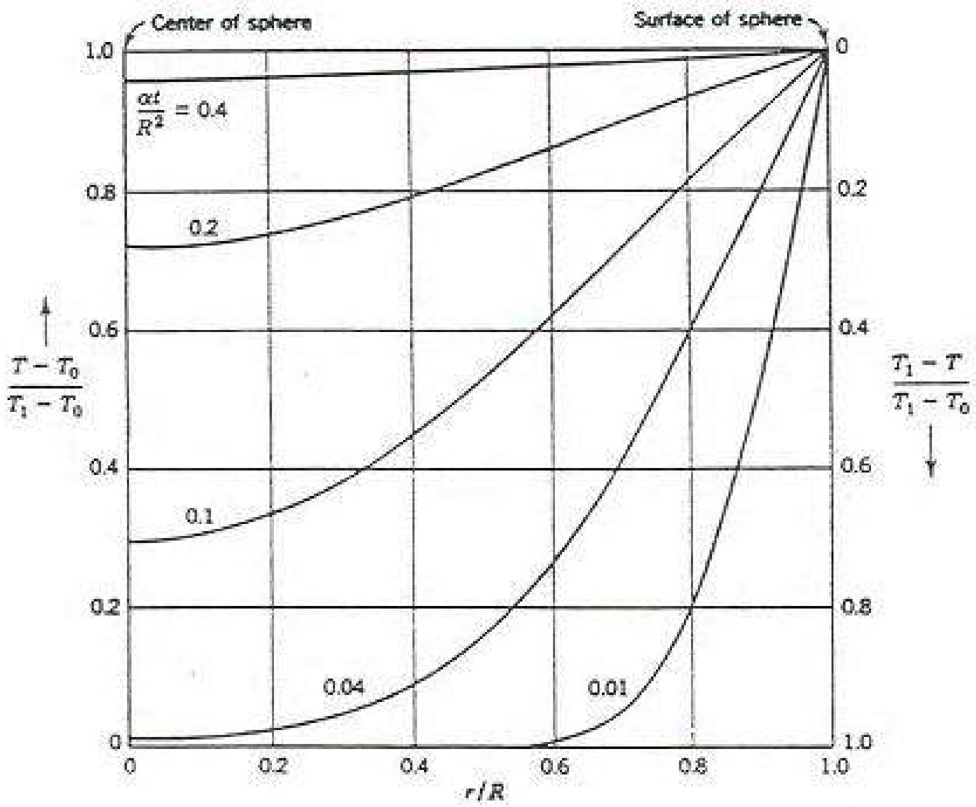
$$\alpha = \frac{k}{\rho C_p} \qquad \text{and} \qquad \text{Fourier Modulus} = \frac{\alpha t}{b^2}$$

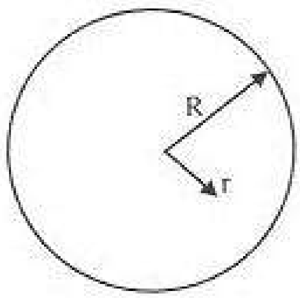
α = thermal diffusivity, m^2/s
k = thermal conductivity, J/s.m.°K
ρ = density, kg/m^3
C_p = specific heat, J/kg.°K
t = time, s
b = ½ of slab thickness, m





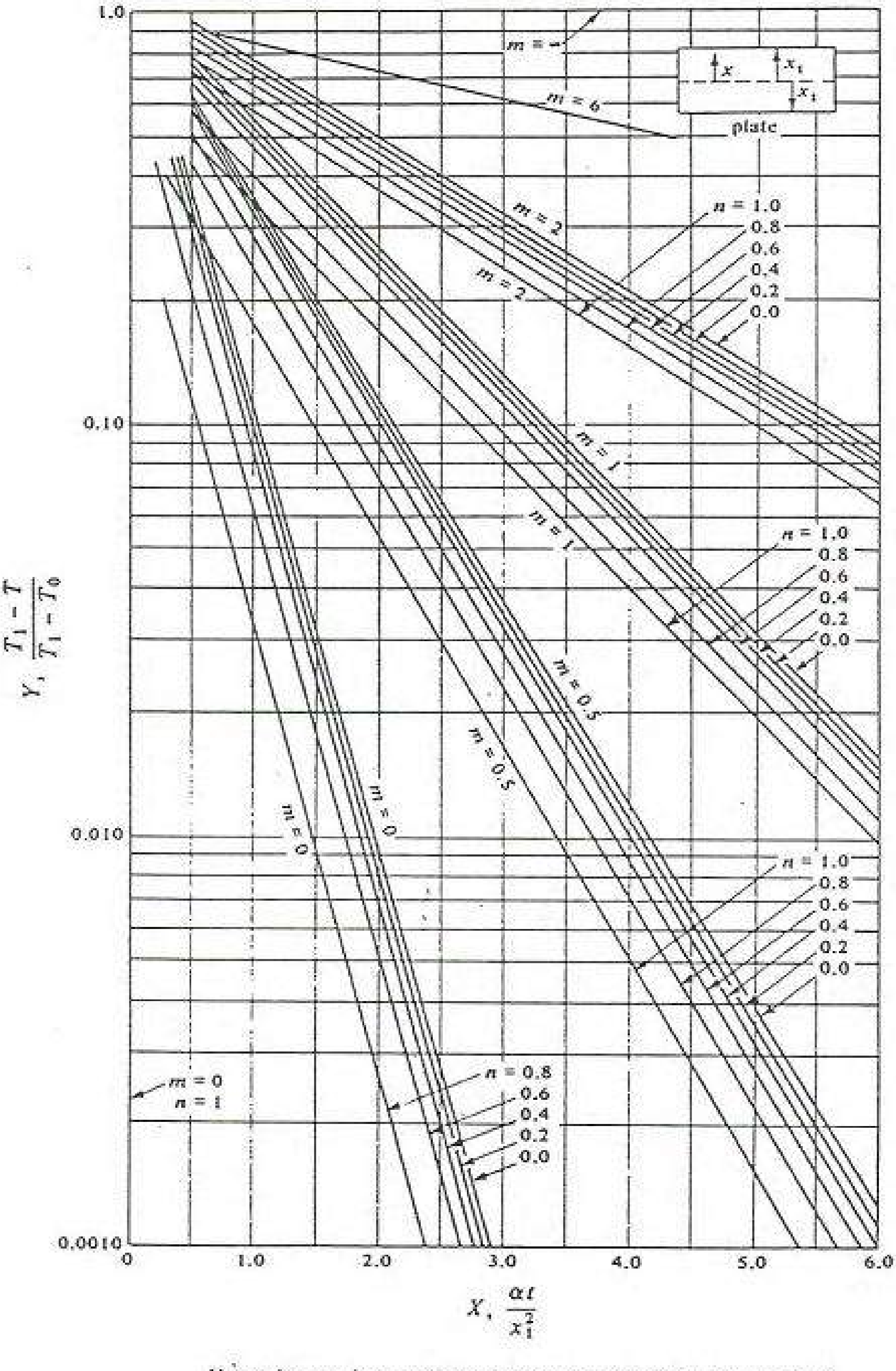
Temperature profiles for unsteady-state heat conduction in a cylinder. T_0 is the initial temperature of the cylinder, and T_1 is the temperature at the surface for $t > 0$. [H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids*, Oxford University Press (1959), p. 200.]





Temperature distribution in a sphere resulting from unsteady-state heat conduction. T_0 is the initial temperature of the sphere, and T_1 is the temperature at the surface for $t > 0$. [H. S. Carslaw and J. C. Jaeger, *Conduction of Heat in Solids*, Oxford University Press (1959), p. 234.]

- Solutions to the heat conduction equations with the appropriate boundary conditions have been presented graphically - pages 113 - 117. These graphs present solutions to *unsteady-state* heat conduction in a large flat plate, a long cylinder and a sphere. From these graphs, one can determine the temperature at any position (location) in the object at any time, t.



Unsteady-state heat conduction in a large flat plate. [*From H. P. Gurney and J. Lurie, Ind. Eng. Chem.,* **15**, *1170 (1923).*]

- For a flat plate, heat is only being conducted in the x-direction.

- The original uniform temperature of the plate is T_0; at time t = 0, the solid is exposed to an ambient temperature T_1 and unsteady - state heat conduction begins. A surface "film" resistance is present therefore ***h*** is finite.

The temperature history at the point where n = 0 (i.e., x = 0 which is the center location) … may be of importance … especially in food processing.

- Therefore, Heisler Charts have been developed to provide a more accurate means of evaluating only the center temperature.

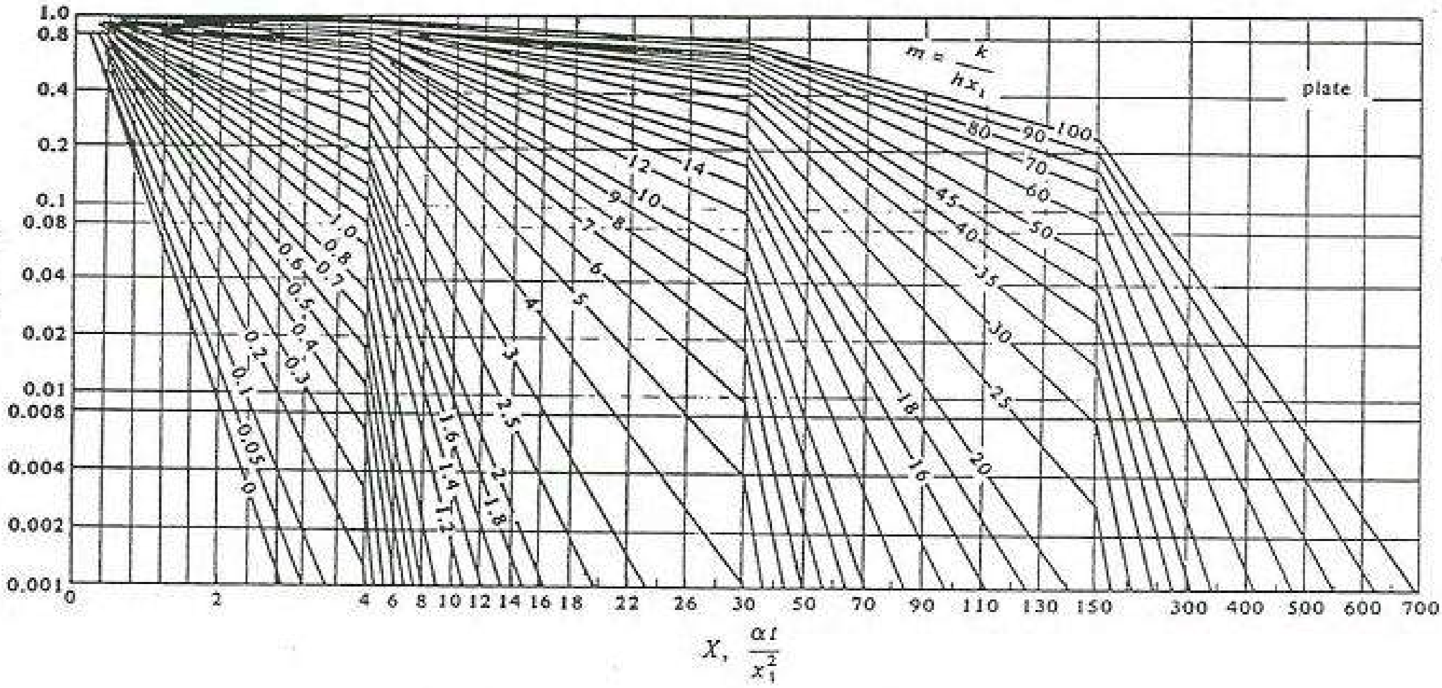
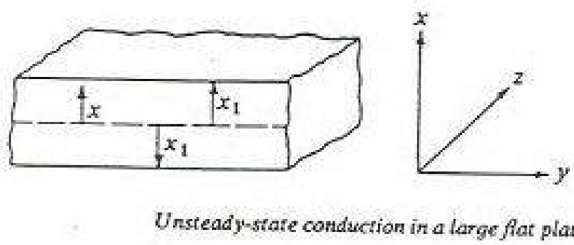


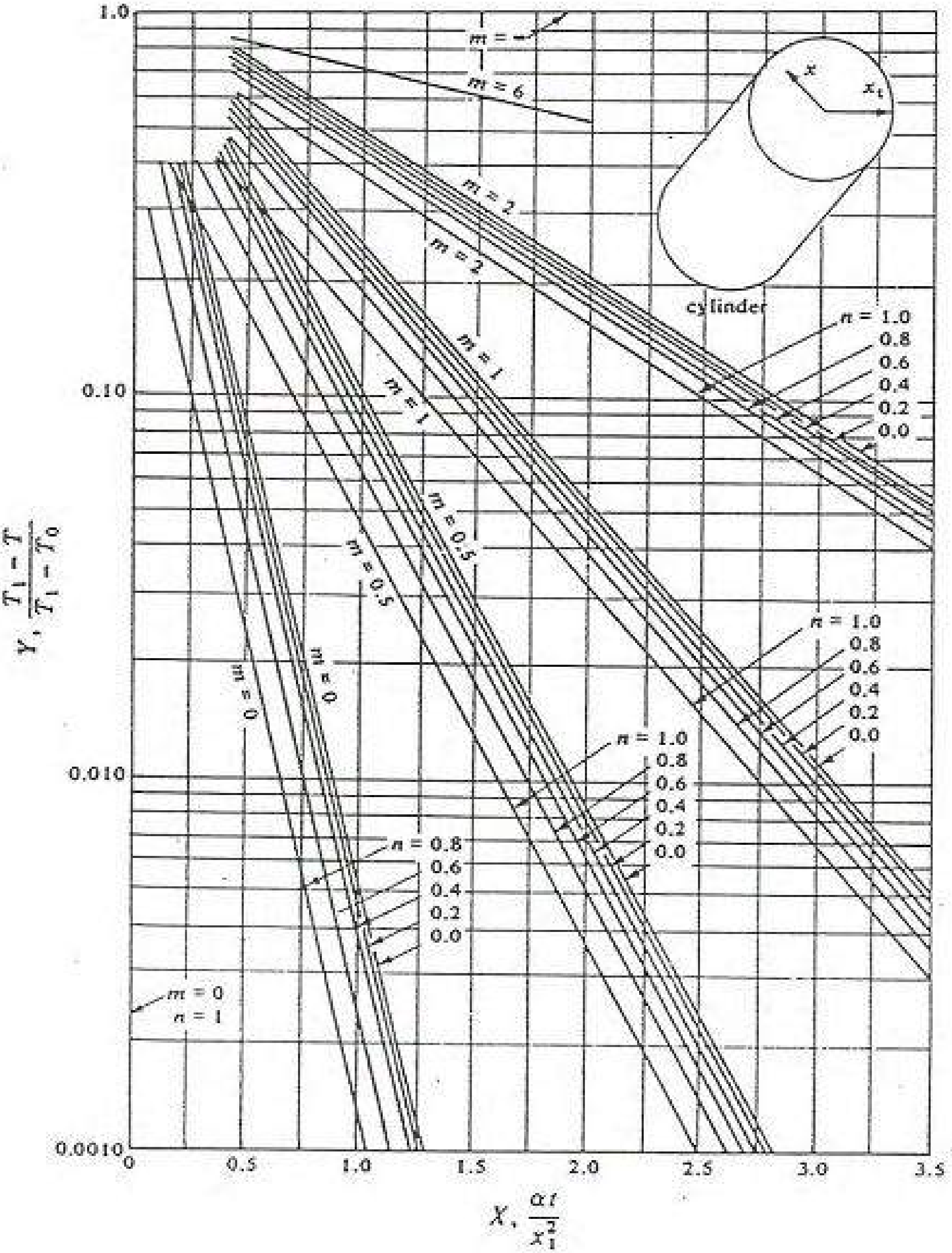
Chart for determining temperature at the center of a large flat plate for unsteady-state heat conduction. [From H. P. Heisler, Trans. A.S.M.E., 69, 227 (1947). With permission.]



Unsteady-state conduction in a large flat plate.

Cylinder

Unsteady-state heat conduction in a long cylinder; conduction occurs only in the r-direction. Conduction at the ends of the cylinder is neglected.



Unsteady-state heat conduction in a long cylinder. [*From H. P. Gurney and J. Lurie, Ind. Eng. Chem.*, 15, *1170* (*1923*).]

Cylinder

For center temperature only:

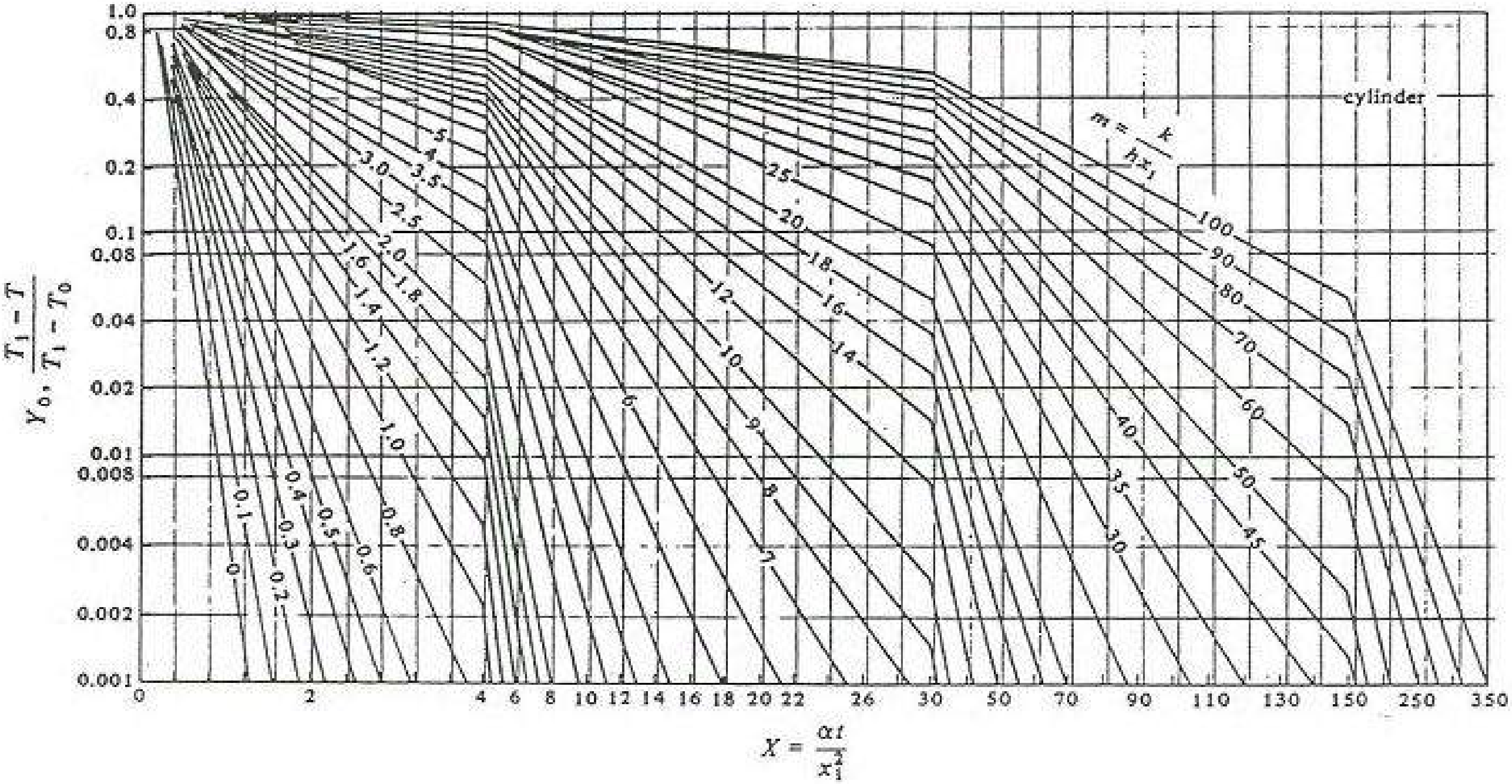
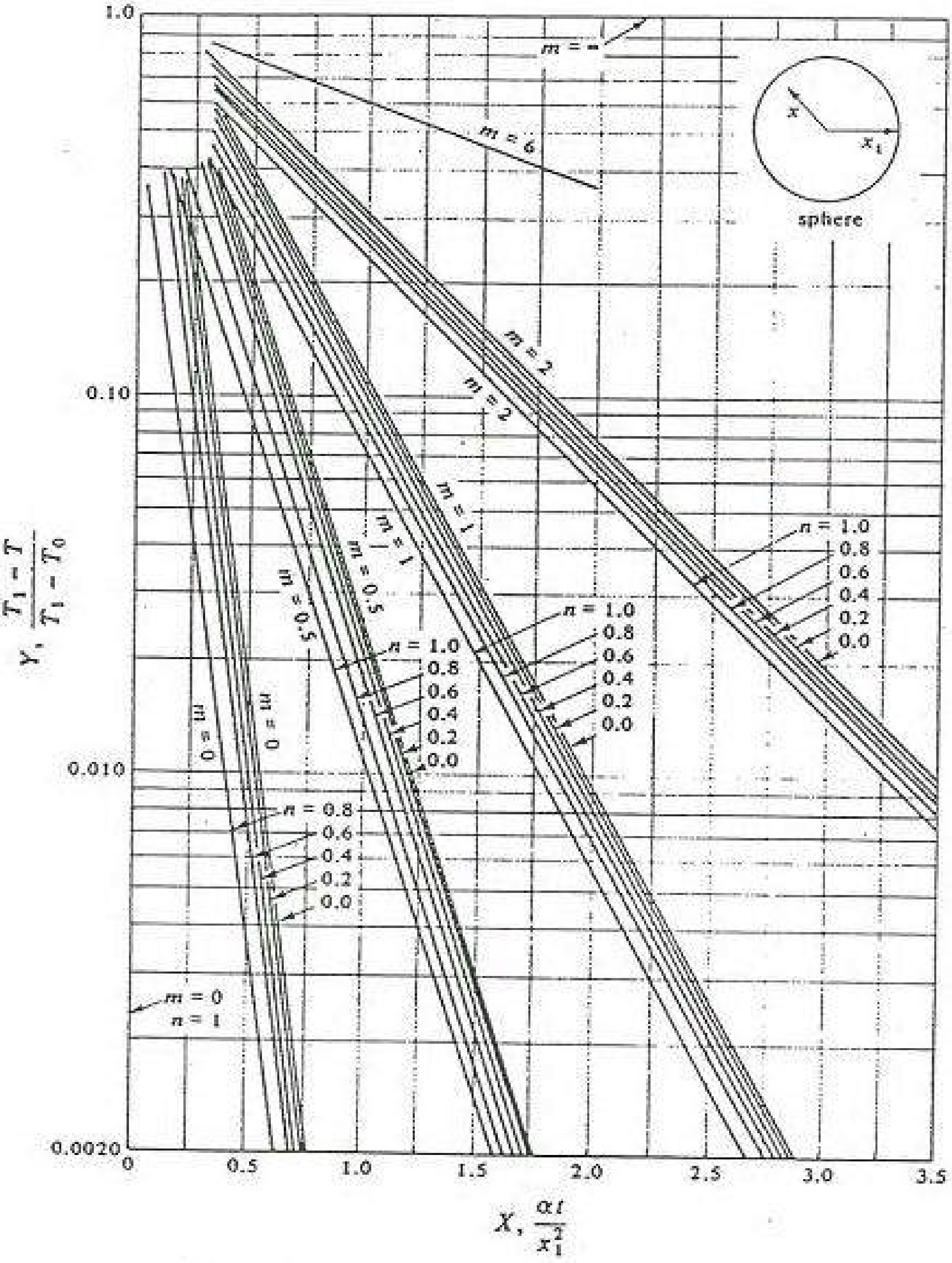


Chart for determining temperature at the center of a long cylinder for unsteady-state heat conduction. [From H. P. Heisler, Trans. A.S.M.E., 69, 227 (1947). With permission.]

Sphere

Unsteady-state heat conduction in a sphere.



Unsteady-state heat conduction in a sphere. [*From H. P. Gurney and J. Lurie, Ind. Eng. Chem.*, 15, *1170* (*1923*).]

Sphere

For center temperature only:

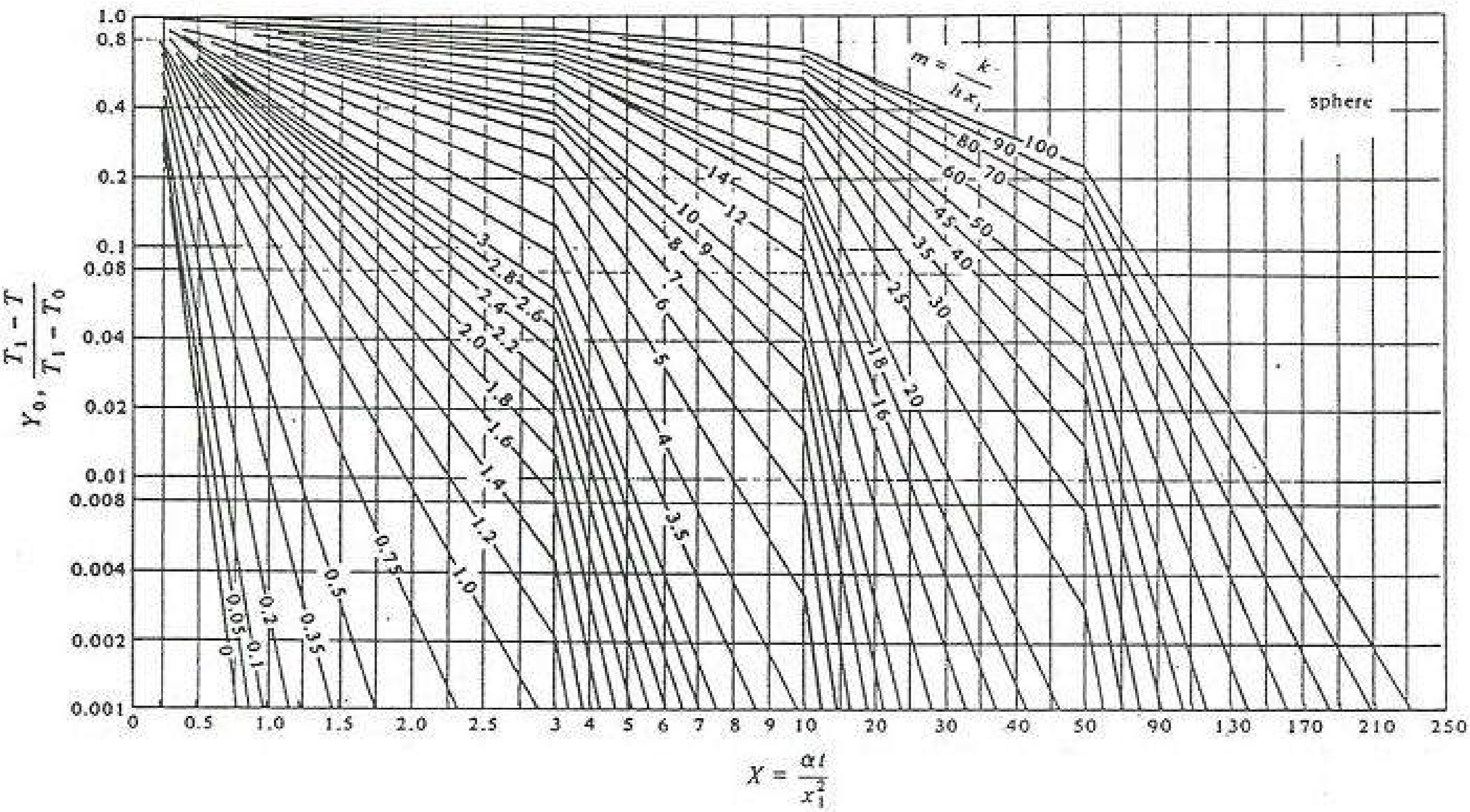


Chart for determining the temperature at the center of a sphere for unsteady-state heat conduction. [From H. P. Heisler, Trans. A.S.M.E., 69, 227 (1947). With permission.]